EXHIBIT I

Skin Rendering Overview

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outline

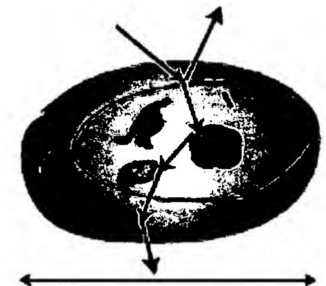
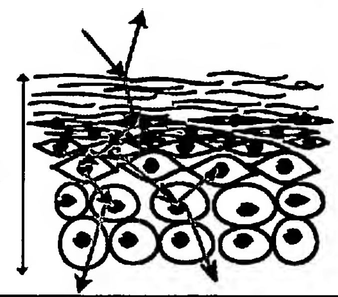
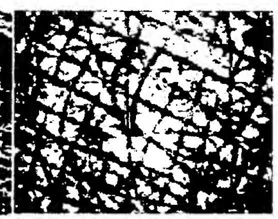
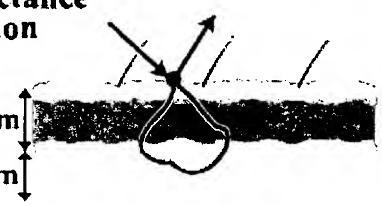
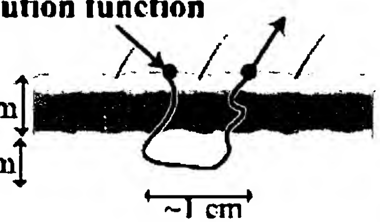
- Introduction
- Property of Skin
  - Skin Appearance
  - Optics property
- Research
  - BRDF
  - Subsurface Scattering && BSSRDF
  - Image/Texture Based Approach
- Problem

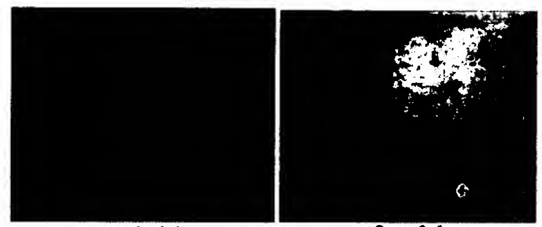
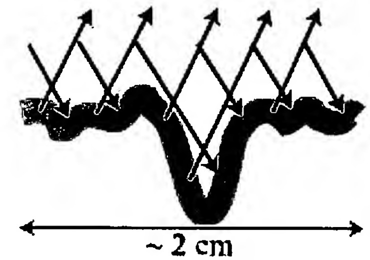
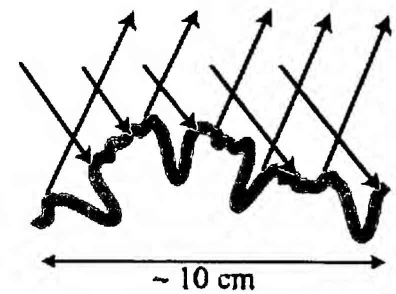
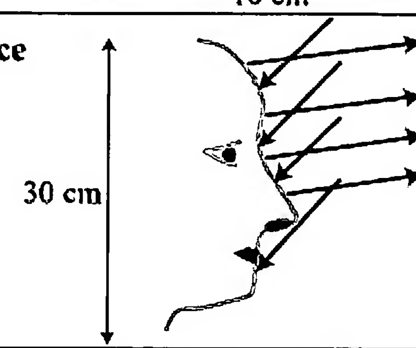
Introduction

- What is Skin Rendering
  - Render skin surface as realistic as possible in any light condition or view direction
- Issue
  - Accuracy
  - Speed

Property of Skin

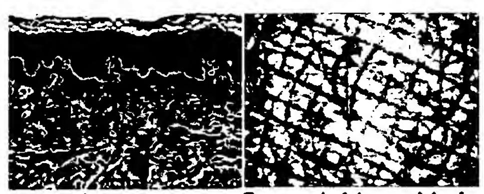
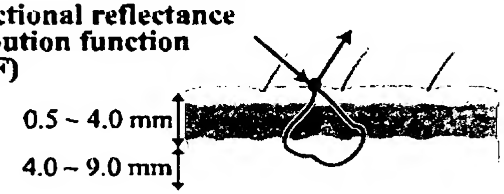
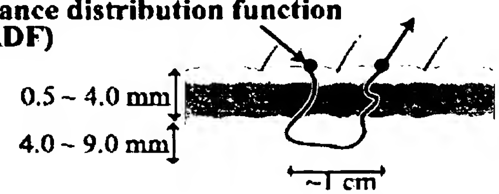
- Skin Appearance
  - Igarashi, T., Nishino, K., and Nayar, S. K.(2005). The Appearance of Human Skin. Technical report#CUCS-024-05, Department of Computer Science, Columbia University 2005
- Skin is the outermost tissue of the body
  - approximately 16, 000 cm^2
  - 8% of the body weight
- Skin has a very complex structure
  - Cells, fibers
  - several different layers

Scale	Level	Physiological / Anatomical Components	Physical Phenomena / Models
Micro	1	**Cellular Level Elements** ▪ keratinocyte ▪ melanocyte ▪ erythrocyte ▪ collagen fiber . . .  keratinocyte *1  collagen fiber *2	**cellular optics** 
	2	**Skin Layers** ▪ epidermis ▪ dermis ▪ subcutis  epidermis *1  dermis *3	**cutaneous optics** 0.04 ~ 1.6mm 
Meso	3	**Skin** ▪ skin surface lipid ▪ hair ▪ skin layers ▪ fine wrinkle . . .  skin layers *3  fine wrinkle and hair	**bidirectional reflectance distribution function (BRDF)** 0.5 ~ 4.0 mm 4.0 ~ 9.0 mm  **bidirectional scattering surface reflectance distribution function (BSSRDF)** 0.5 ~ 4.0 mm 4.0 ~ 9.0 mm 

Macro	4	**Skin Features** ▪ wrinkle ▪ pore ▪ mole ▪ freckle...  wrinkle freckle	**bidirectional texture function (BTF)** 
	5	**Body Regions** ▪ nose ▪ finger ▪ elbow ▪ knee ...  nose finger elbow	**region appearance** 
	6	**Body Parts** ▪ face ▪ arm ▪ leg ▪ torso ...  face arm	**part appearance** 

Property of Skin

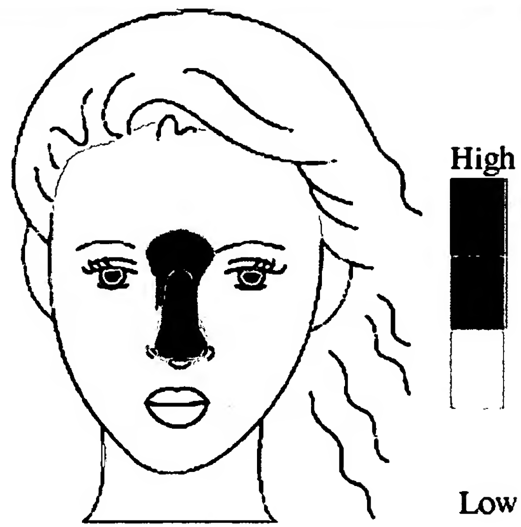
- Optics property
  - Focus on meso scale
    - Hair
    - Skin surface lipid film (SSLF)
    - Fine wrinkle
    - mole, pore, spot etc..
    - Skin layers (epidermis, dermis, subcutis)

Meso	3	**Skin** • skin surface lipid • hair • skin layers • fine wrinkle . . .  skin layers •3 fine wrinkle and hair	**bidirectional reflectance distribution function (BRDF)**  **bidirectional scattering surface reflectance distribution function (BSSRDF)** 

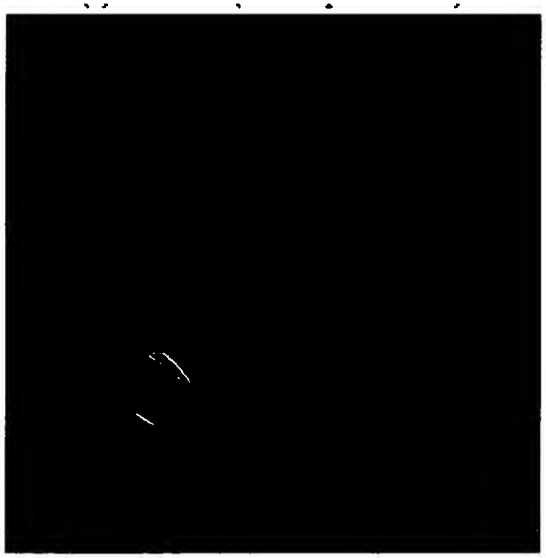
Hair

Skin surface lipid film (SSLF)

- 表面油脂
  - T字部位



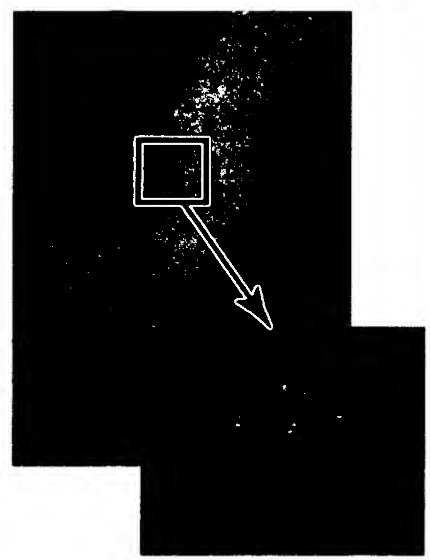
- Specular Map

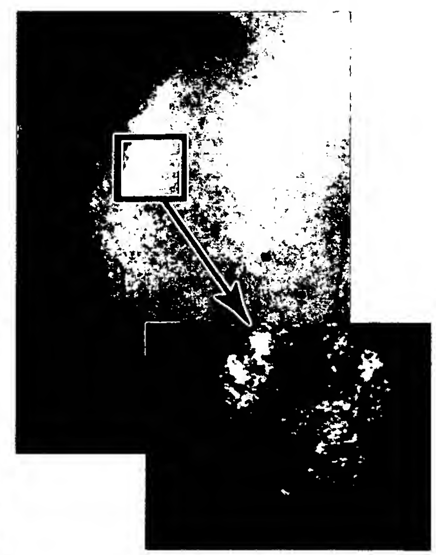


Fine wrinkle

- 皮膚表面非常細微的皺摺

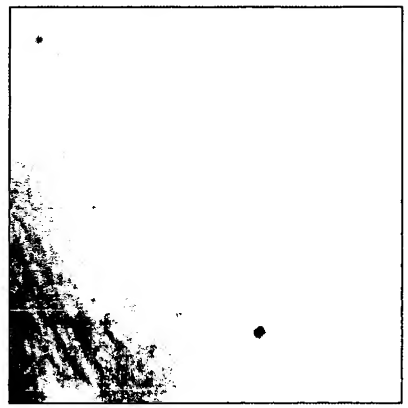
- fine wrinkle會造成反射程度的不同

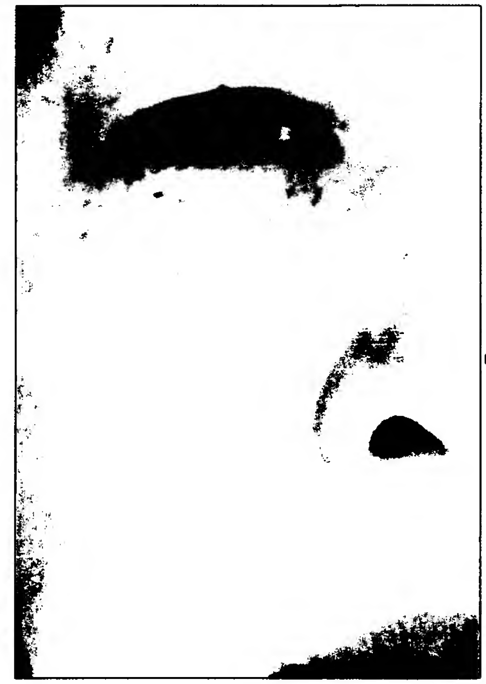




mole, pore, spot etc..

- 皮膚上的特徵
  - 痣
  - 疤痕
  - 毛孔
  - 等等





- Texture/Normal Map

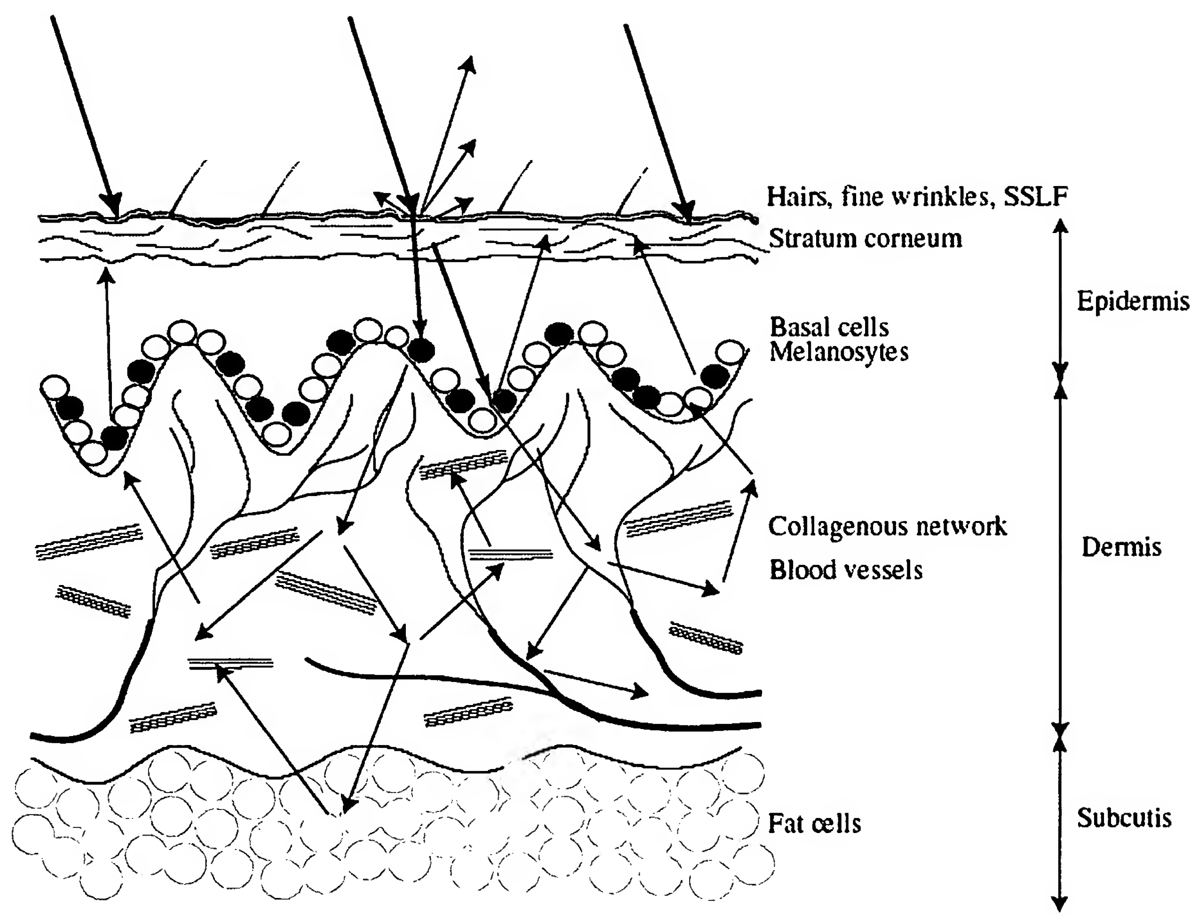
Skin layers

- Skin layer
  - epidermis (0.2 mm)
  - dermis (1 to 4 mm)
  - subcuit (4 to 9 mm)
- Composition of layers is too complex
  - difficult for quantitative analysis of the optical properties of skin
  - consider epidermis & dermis as independent optical media
    - *melanin layer* (epidermis)
    - *hemoglobin layer* *(dermis)*

Optics property of skin layers

- Assumption
  - absorption && scattering are uniformly distributed over skin layer
  - anisotropy of the light propagation caused by preferential alignments of collagen fibers is negligible

Optics property of skin layers



Epidermis

- A more or less transparent layer that does not produce strong enough scattering
- Significant absorption depends on the volume of melanin

- Few scattering
- Much absorption (depends on melanin)
- Melanin layer

Dermis

- Significant amount of multiple scattering in the vast network of collagen fibers
- Significant absorption by hemoglobin
- The scattering properties of the dermis depend on the wavelength of light
  - longer wavelength can penetrate deeper
- Can be described as a combination of two layers
  - *multiple scattering layer*
  - *hemoglobin layer*

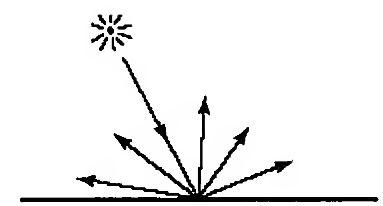
Subsurface Scattering Effect

Research on Skin Rendering

- BRDF
- Subsurface Scattering && BSSRDF
- Image/Texture Based Approach

BRDF

- Bidirectional Reflectance Distribution Function
- 光在表面入射光線量與反射光線量的比例

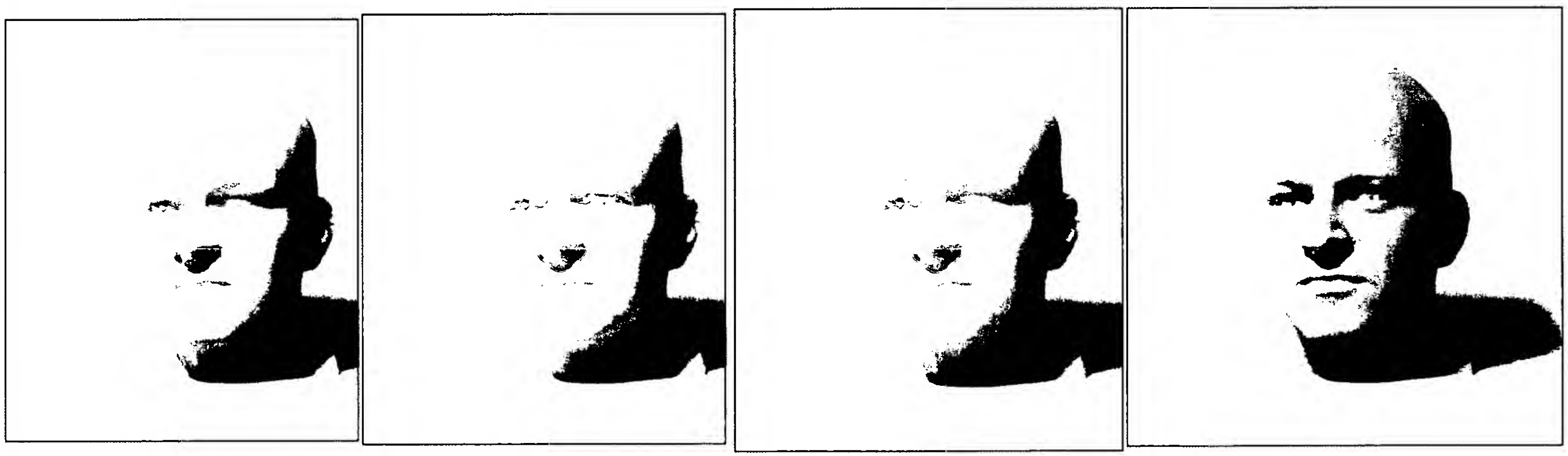


$$L_o(x_o,\omega_o) = \int_{2\pi} \mathrm{L}(x_i,\omega_i)(\vec{n}_i \cdot \vec{\omega}_i) f(\omega_i,\omega_o) d\omega_i$$

- Dana, K. J., Ginneken, B. V., Nayar, S. K., and Koenderink, J. J.(1997). Reflectance and Texture of Real-World Surfaces. *Proceedings of the IEEE Computer Society conference on Computer Vision and Pattern Recognition*, June 1997
- Marschner, S. R., Westin, S.H., Lafortune, E. P. F., Torrance, K. E.,and Greenberg, D. P.(1999). Image-based BRDF measurement including human skin. In*Proceedings of 10th Eurographics Workshop onRendering*, pages 139–152, 1999.

Skin color using BRDF

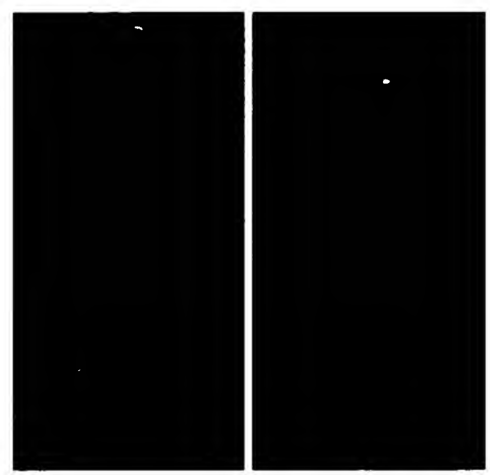
- 43 Caucasian male 2 6 Caucasian male 9 girl 23 male from India



- Looks not so realistic
- Miss count the effect of subsurface scattering in skin layer

Subsurface Scattering && BSSRDF

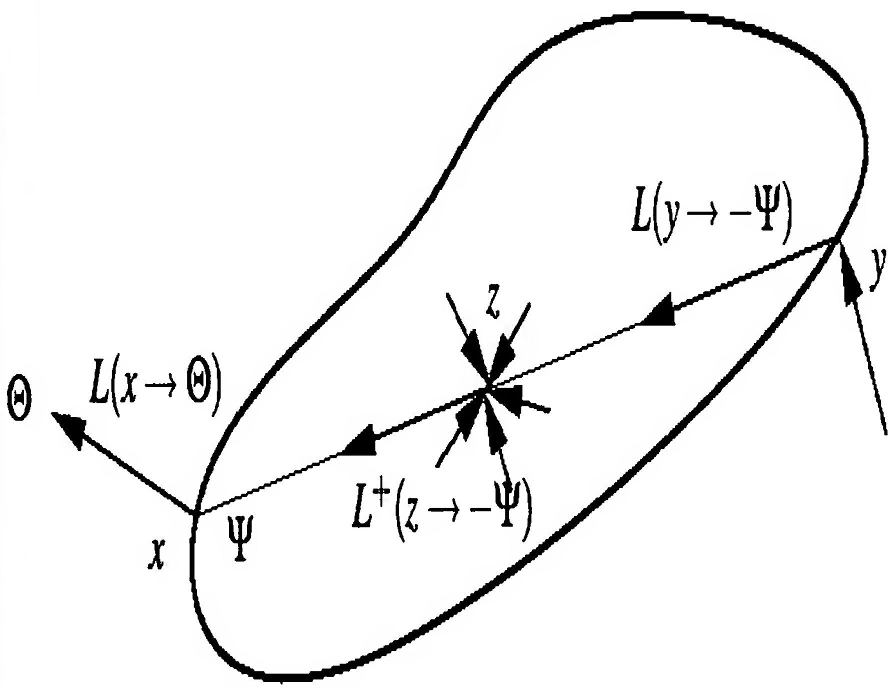
- Participating Media
- Volume Rendering Equation
- Research on Subsurface Scattering
- Research on BSSRDF
- Skin Rendering using BSSRDF



Jade

Participating Media

- Optical properties which affect the light
  - Absorption, emission, scattering



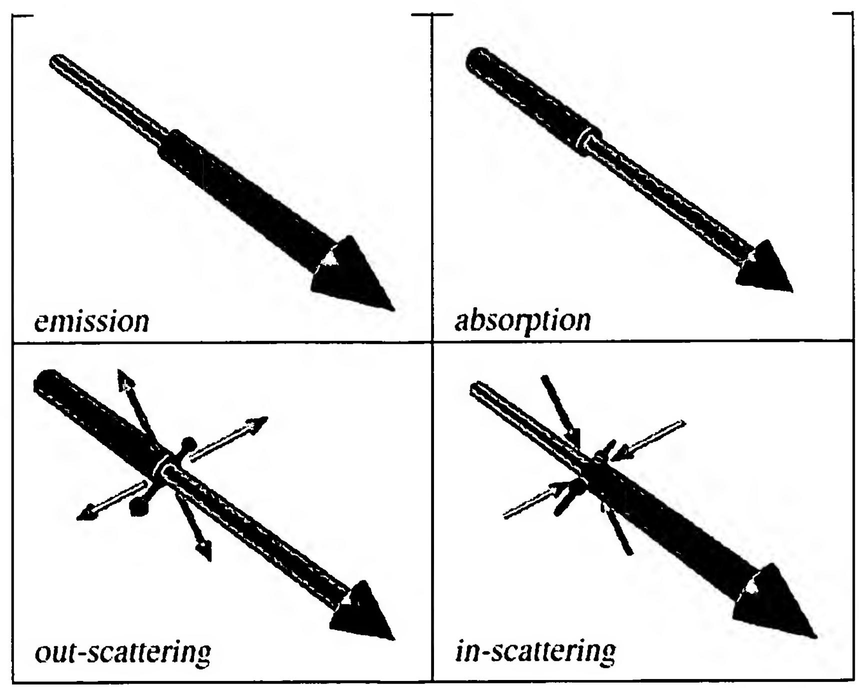
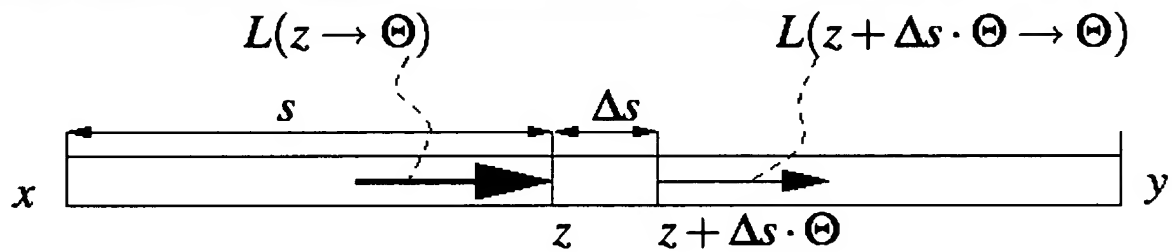


Fig. 1 Interaction of light in a participating medium.

Properties of Participating Media

- Emission
  - Volume emittance function $\varepsilon(x)\ [W/m^3]$
  - Volume emittance radiance $dL^e(x \to \theta) = \frac{\varepsilon(x)}{4\pi} ds\ [W/m^2 \cdot sr]$
- Absorption
  - Absorption coefficient $\sigma_a(x)\ [1/m]$
  - One photon traveling a distance Δs in media has chance $\sigma_a \cdot \Delta s$ be absorbed
  - Mean free path $1/\sigma_a(x)\ [m]$

Properties of Participating Media



- 極小變動距離下，光線量的衰減可以表示為

$$L(z + \Delta s \cdot \theta \to \theta) = L(z \to \theta)(1 - \sigma_a(z) \cdot \Delta s)$$

- 取極限值後，可以得到

$$dL(z \to \theta)/ds = -\sigma_a(z) L(z \to \theta)$$

- 將極限值從X積分到Z，可推導出X和Z光線量關係

$$L(z \to \theta) = L(x \to \theta) \exp\left(-\int_x^z \sigma_a(x) ds \right)$$

- 材質為同質性的話，則形成常見的指數函式

$$L(z \to \theta) = L(x \to \theta) e^{-\sigma_a \cdot s}$$

Properties of Participating Media

- Scattering
  - Scattering coefficient $\sigma_s(x)$ $[1/m]$
  - One photon traveling a distance Δs in media has chance $\sigma_s \cdot \Delta s$ be scattered.
- Extinction
  - extinction coefficient $\sigma_t(x) = \sigma_a(x) + \sigma_s(x)$ $[1/m]$
- Albedo
  - relative importance of scattering vs absorption

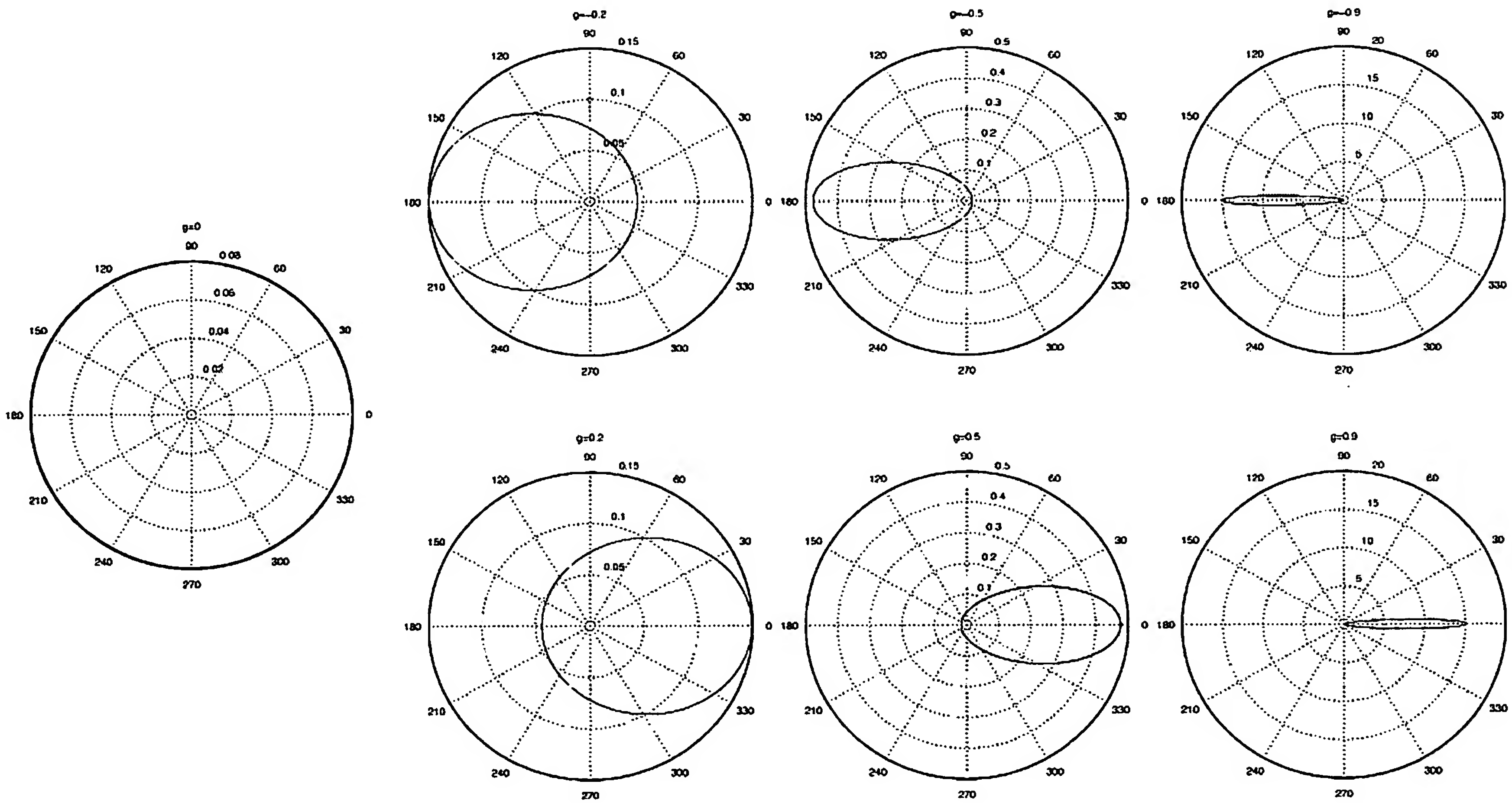
$$\alpha(x) = \sigma_s(x) / \sigma_t(x)$$

Properties of Participating Media

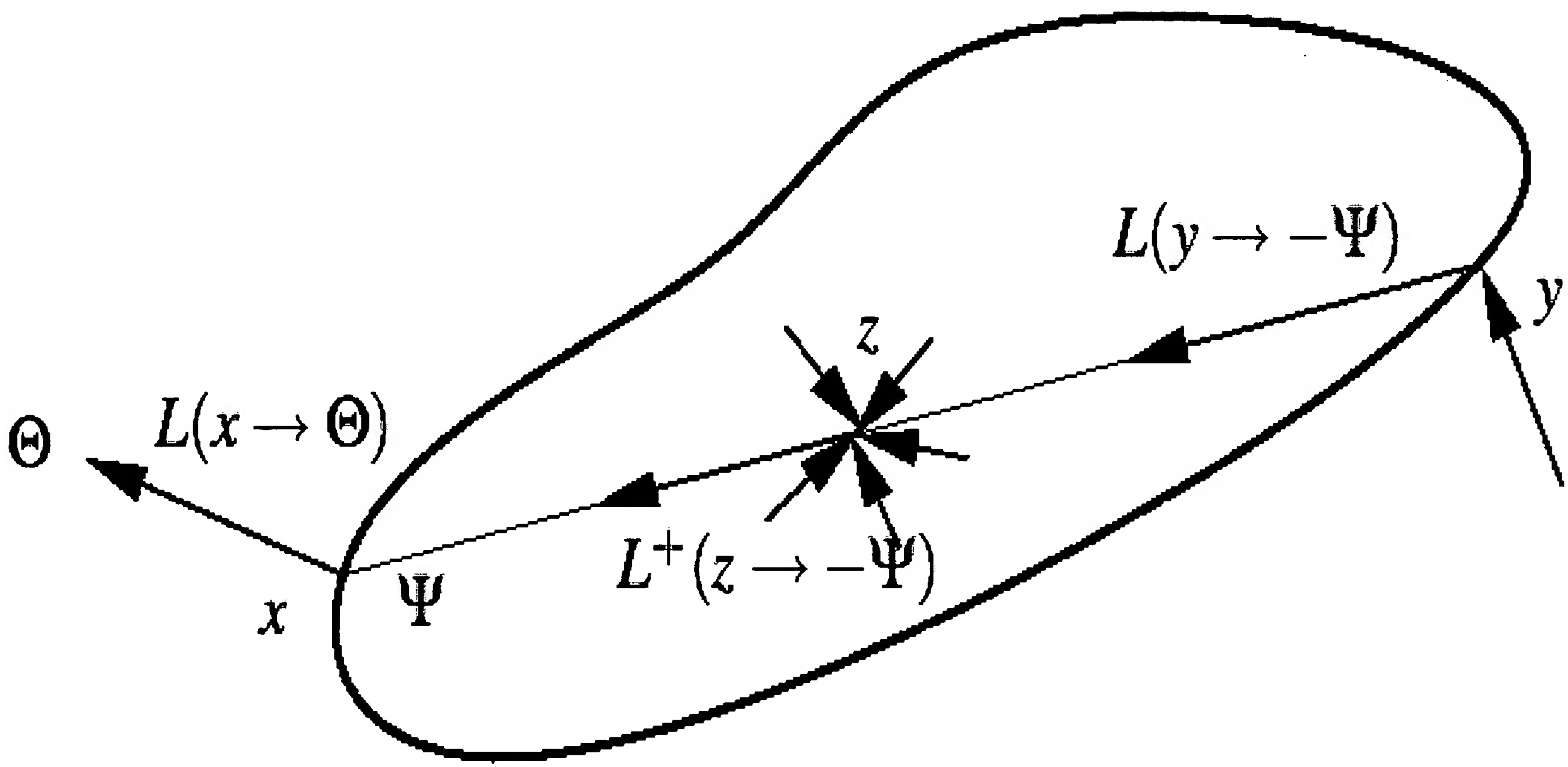
- Phase function $\rho(x, \Psi \leftrightarrow \Theta)$
  - describe the distribution of the scattered light in participating media.
  - Normalized $\int_{\Omega} \rho(x, \Psi \leftrightarrow \Theta) d\Theta = 1$
  - Reciprocity $\rho(x, \Psi \leftrightarrow \Theta) = \rho(x, \Theta \leftrightarrow \Psi)$
  - The mean cosine $g = \int_{4\pi} (\Theta \cdot \Psi) \rho(x, \Theta \leftrightarrow \Psi) d\Psi$

Properties of Participating Media

- Greenstein phase function



Volume Rendering Equation



Volume Rendering Equation

- 如何表示再Participating Media內部，光的Rendering Equation ??
- 考慮在內部光從 X往Ψ方向的光線量　$L_p(x \to -\Psi)$

$$L_p(x \to -\Psi) = L(y \to -\Psi) r(x,y) + \int_y^x L^+(z \to -\Psi) r(x,y) dr$$

$$r(x,y) = \exp\left(-\int_x^y \sigma_t(r) dr \right)$$

- $L^+(z \to \Psi)$ 表示內部經由In-Scattering而聚集的光線量

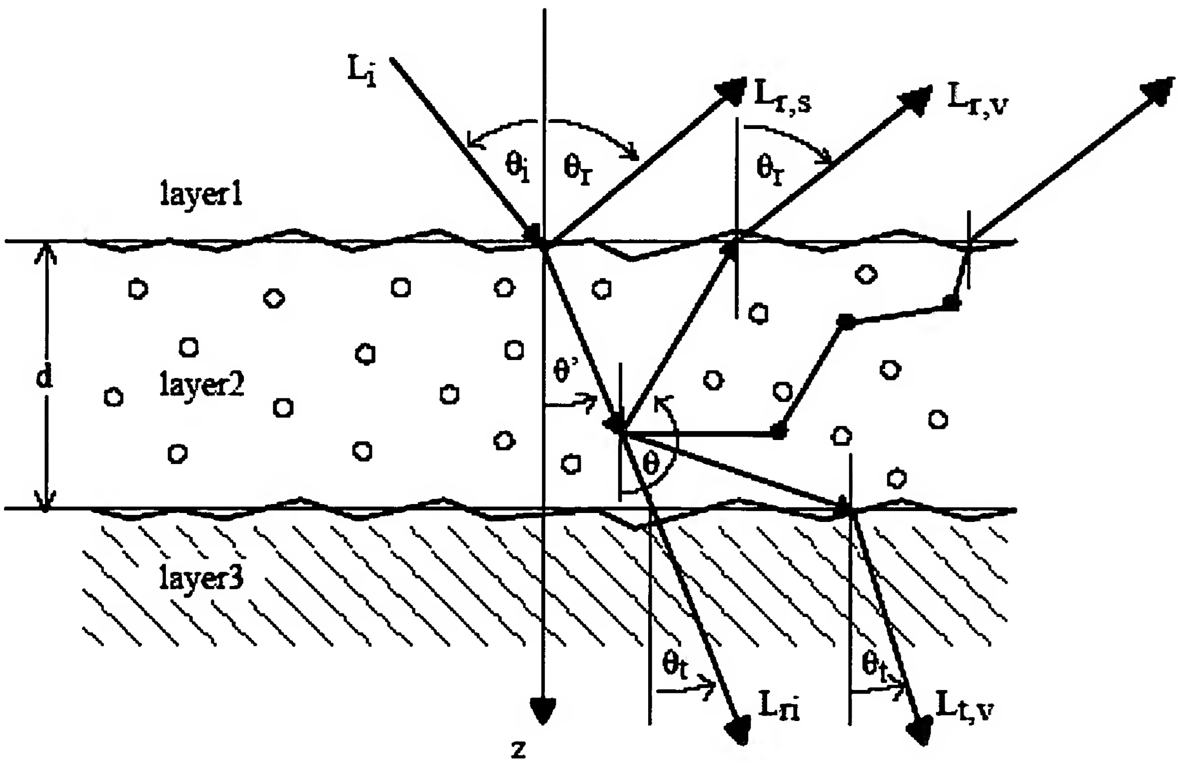
$$L^+(z \to \Psi) = L^e(z) + \int_\Omega \sigma_t(z) \rho(x, \Psi \leftrightarrow \Theta) L_p(z \to \Theta) d\Theta$$

- 最後光經過折射穿透出材質表面

$$L(x \to \Theta) = L_e(x \to \Theta) + \int_\Omega L_p(x \to \Psi) F_t(\Psi \to \Theta) d\Psi$$

Research on Subsurface Scattering

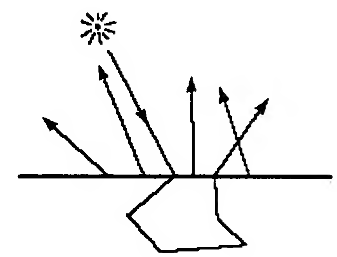
- Pat Hanrahan & Wolfgang Krueger (1993) Reflection from Layered Surfaces due to Subsurface Scattering. In *Proceedings of the 20th annual conference on Computer graphics and interactive technique*



Research on BSSRDF

- Jensen, H. W., Marschner, S. R., Levoy, M., and Hanrahan, P.A.(2001). A Practical Model for Subsurface Light Transport. *Proceedings of SIGGRAPH 2001*
- Bidirectional Surface Scattering Reflectance Distribution Function (BSSRDF)
- 提出BSSRDF 模擬光進入表面後，經過表面下散射後，透射出表面的光線量比例

$$L_o(x_o,\vec{\omega}_o) = \int_A \int_{2\pi} S(x_i,\vec{\omega}_i,x_o,\vec{\omega}_o) L(x_i,\vec{\omega}_i)(\vec{n}_i \cdot \vec{\omega}_i)\, d\vec{\omega}_i\, dA_{x_i}$$



- contributed by two terms
  - Single scattering term
  - Diffuse multiple scattering term

$$S(x_i,\vec{\omega}_i,x_o,\vec{\omega}_o) = S^{(1)}(x_i,\vec{\omega}_i,x_o,\vec{\omega}_o) + S_d(x_i,\vec{\omega}_i,x_o,\vec{\omega}_o)$$

Multi-Scattering

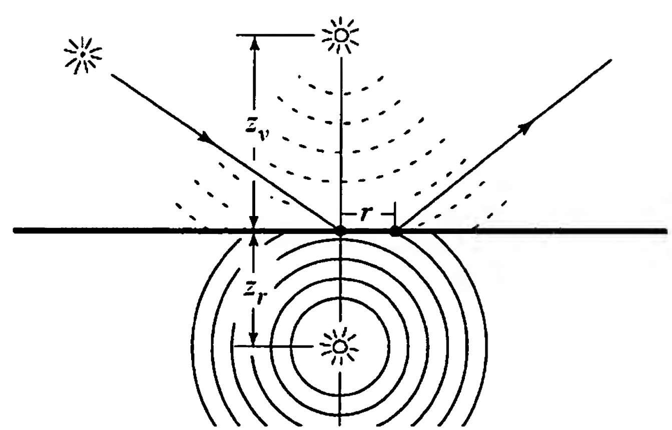
$$S_d(x_i, \vec{\omega}_i, x_o, \vec{\omega}_o) = \frac{1}{\pi} F_t(\eta, \vec{\omega}_i) R_d(\| x_i - x_o \|) F_t(\eta, \vec{\omega}_o)$$

- $R_d(\| x_i - x_o \|)$ is dipole function
  - Related to the distance of incoming and outgoing point

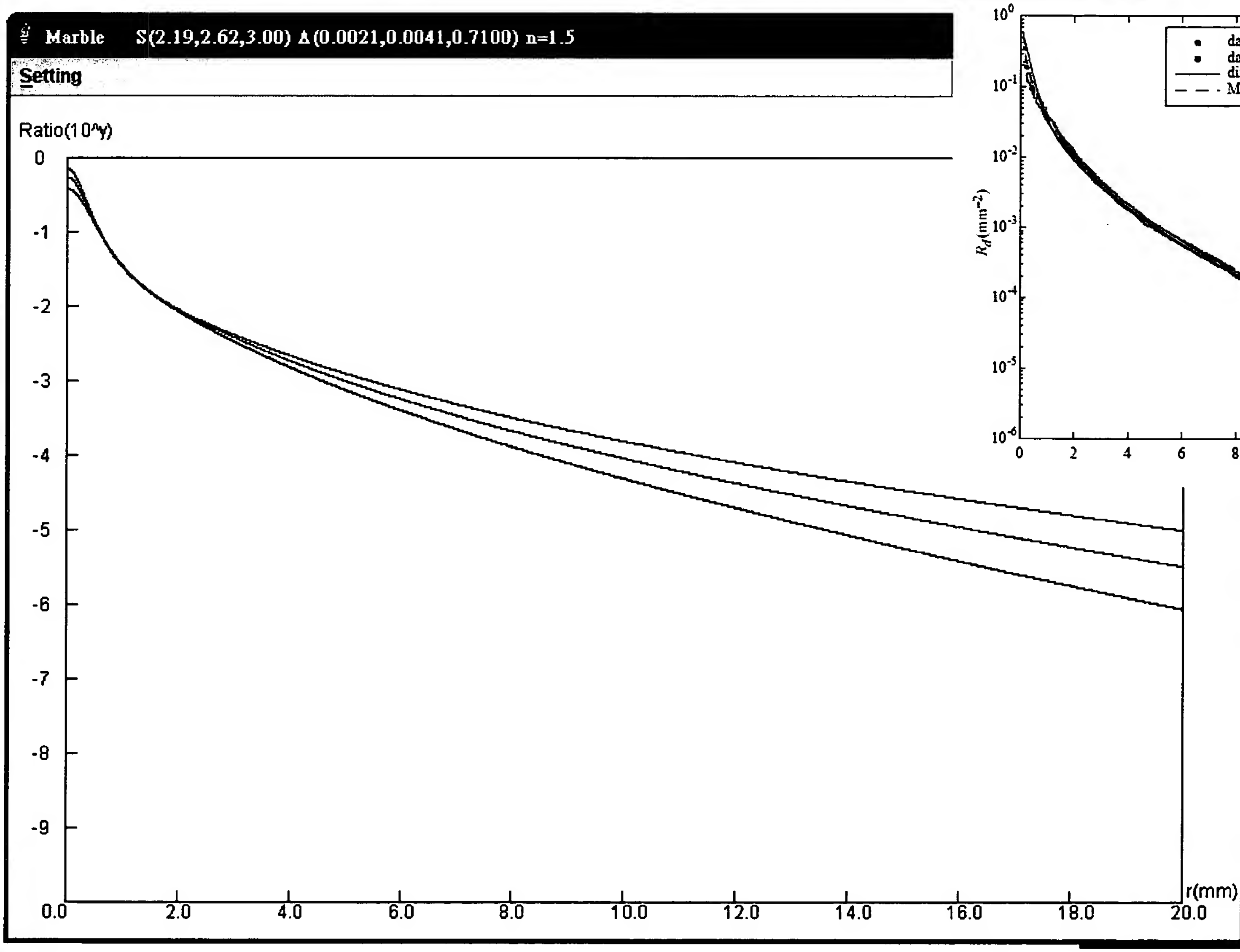
$$R_d(\| x_i - x_o \|) = \frac{\alpha'}{4\pi}\left[z_r(1 + \sigma_{tr} \cdot d_r)\frac{e^{-\sigma_{tr} \cdot d_r}}{d_r^{\,3}} + z_v(1 + \sigma_{tr} \cdot d_v)\frac{e^{-\sigma_{tr} \cdot d_v}}{d_v^{\,3}} \right]$$

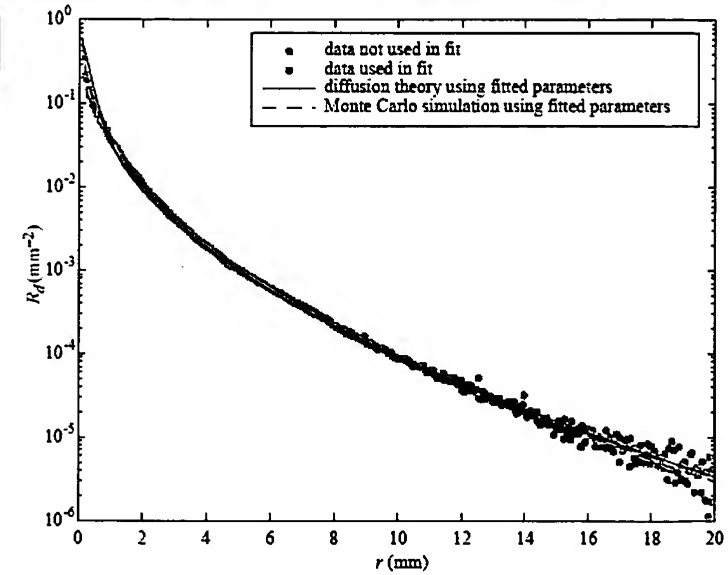
$\sigma_{tr} = \sqrt{3\sigma_a \sigma'_t}$ $\quad \sigma'_t = \sigma_a + \sigma'_s$ $\quad \sigma'_s = \sigma_s(1-g)$ $\quad \alpha' = \sigma'_s / \sigma'_t$

$z_r = 1/\sigma'_t$ $\qquad z_v = z_r(1 + 4A/3)$



Multi-Scattering





Coefficients of BSSRDF

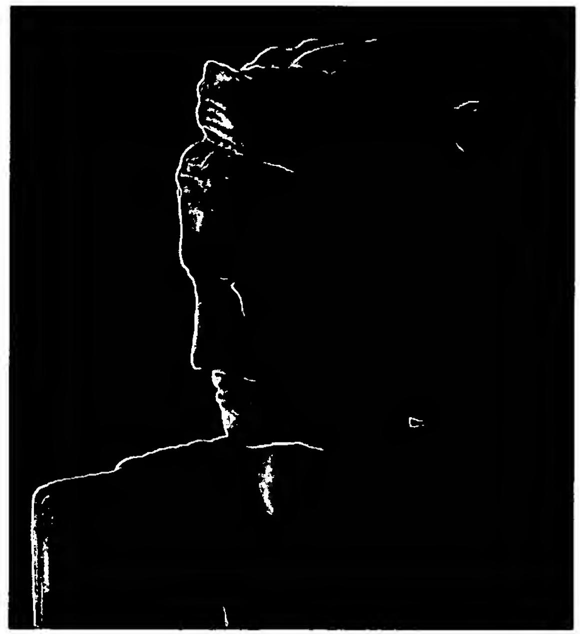
Material	σ_s' [mm^{-1}]			σ_a [mm^{-1}]			Diffuse Reflectance			η
	R	G	B	R	G	B	R	G	B	
Apple	2.29	2.39	1.97	0.0030	0.0034	0.046	0.85	0.84	0.53	1.3
Chicken1	0.15	0.21	0.38	0.015	0.077	0.19	0.31	0.15	0.10	1.3
Chicken2	0.19	0.25	0.32	0.018	0.088	0.20	0.32	0.16	0.10	1.3
Cream	7.38	5.47	3.15	0.0002	0.0028	0.0163	0.98	0.90	0.73	1.3
Ketchup	0.18	0.07	0.03	0.061	0.97	1.45	0.16	0.01	0.00	1.3
Marble	2.19	2.62	3.00	0.0021	0.0041	0.0071	0.83	0.79	0.75	1.5
Potato	0.68	0.70	0.55	0.0024	0.0090	0.12	0.77	0.62	0.21	1.3
Skimmilk	0.70	1.22	1.90	0.0014	0.0025	0.0142	0.81	0.81	0.69	1.3
Skin1	0.74	0.88	1.01	0.032	0.17	0.48	0.44	0.22	0.13	1.3
Skin2	1.09	1.59	1.79	0.013	0.070	0.145	0.63	0.44	0.34	1.3
Spectralon	11.6	20.4	14.9	0.00	0.00	0.00	1.00	1.00	1.00	1.3
Wholemilk	2.55	3.21	3.77	0.0011	0.0024	0.014	0.91	0.88	0.76	1.3

Result

BRDF **BSSRDF**

Result

(a) BRDF



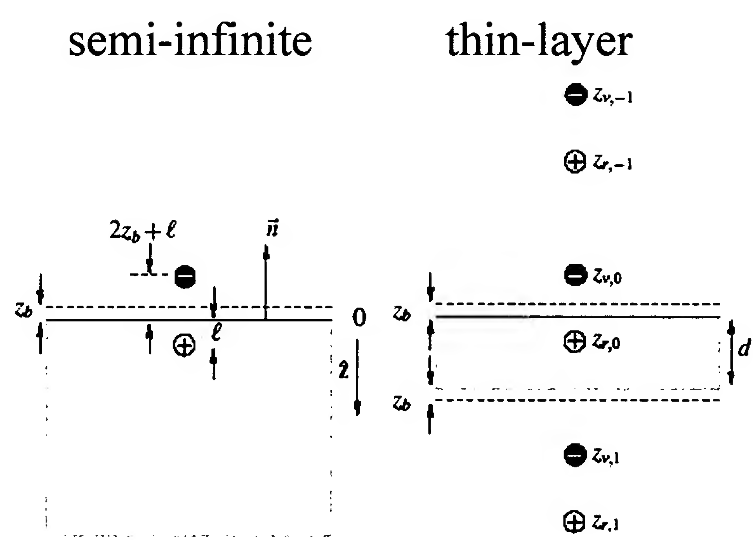
(b) BSSRDF(5min)

(c) Monte Carlo(1250min)

Demo 1 Demo 2

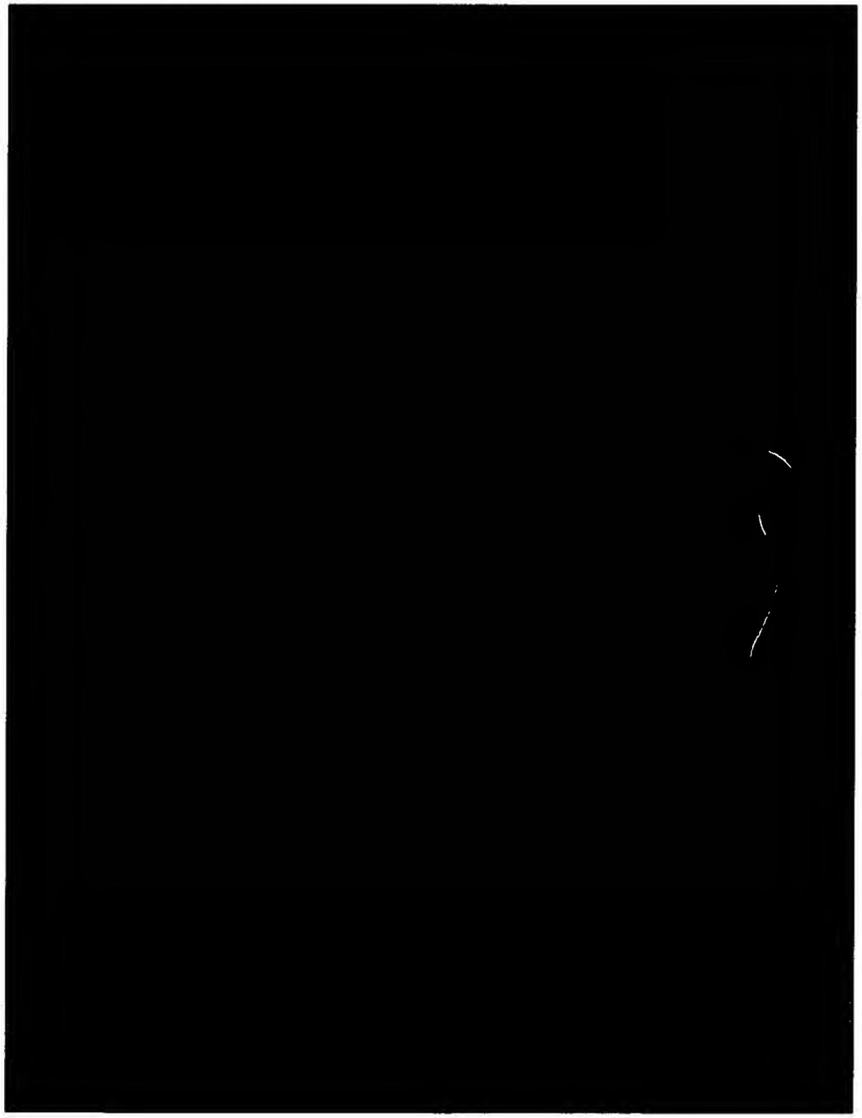
Research on BSSRDF

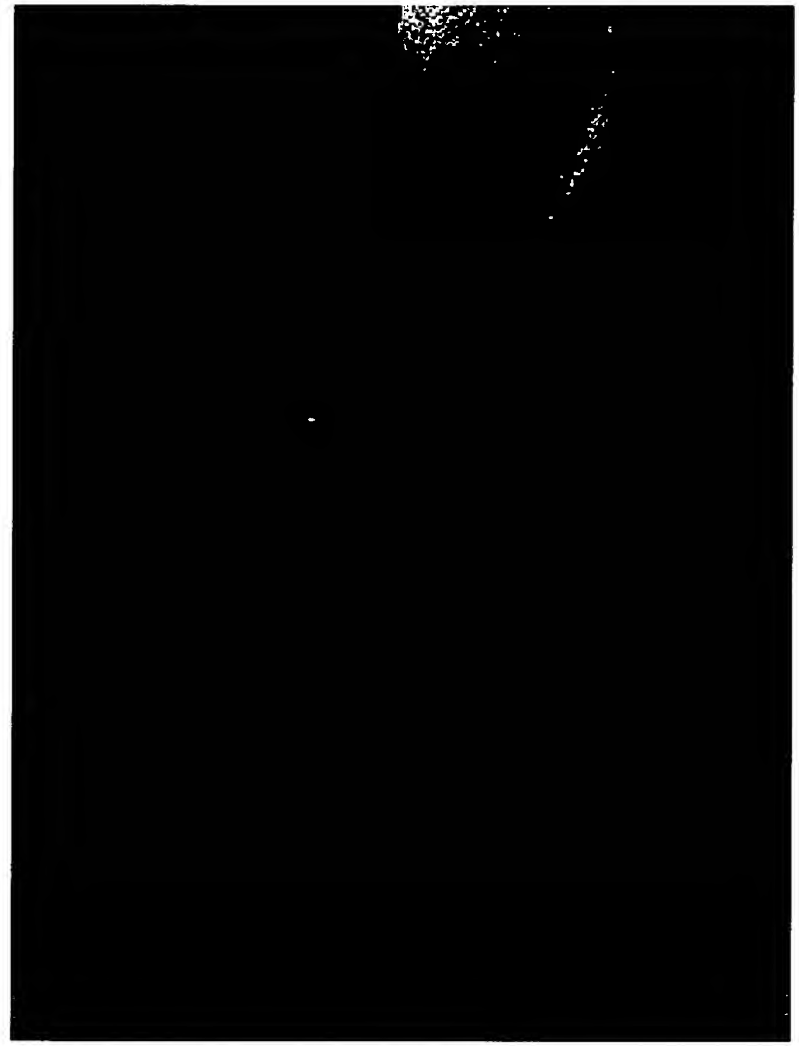
- Donner, C., and Jensen, H. W.(2005). Light Diffusion in Multi-Layered Translucent Materials. *Proceeding of SIGGRAPH 2005*



$$T_{12} = T_1 * T_2 + T_1 * R_2 * \mathrm{R}_1 * T_2 + T_1 * R_2 * \mathrm{R}_1 * R_2 * \mathrm{R}_1 * T_2 + \Lambda$$

Research on BSSRDF





Backlit close-up of the left ear

Research on BSSRDF

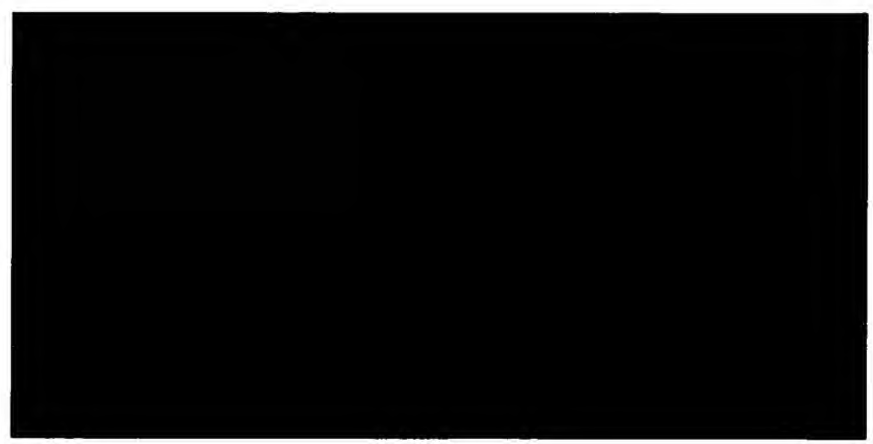
- Jensen, H. W., and Buhler, J.(2002). A Rapid Hierarchical Rendering Technique for Translucent Materials. *ACM Transactions on Graphics*, pages 576-581.

$$L_o(x_o,\vec{\omega}_o)=\frac{1}{\pi}\int_A\int_{2\pi}L(x_i,\vec{\omega}_i)(\vec{n}_i\cdot\vec{\omega}_i)F_t(\eta,\vec{\omega}_i)R_d(\| x_i-x_o \|)F_t(\eta,\vec{\omega}_o)d\vec{\omega}_i dA_{x_i}$$

$$L_o(x_o,\vec{\omega}_o)=F_t(\eta,\vec{\omega}_o)\int_A E_{in}(x_i)R_d(\| x_i-x_o \|)dA_{x_i}$$

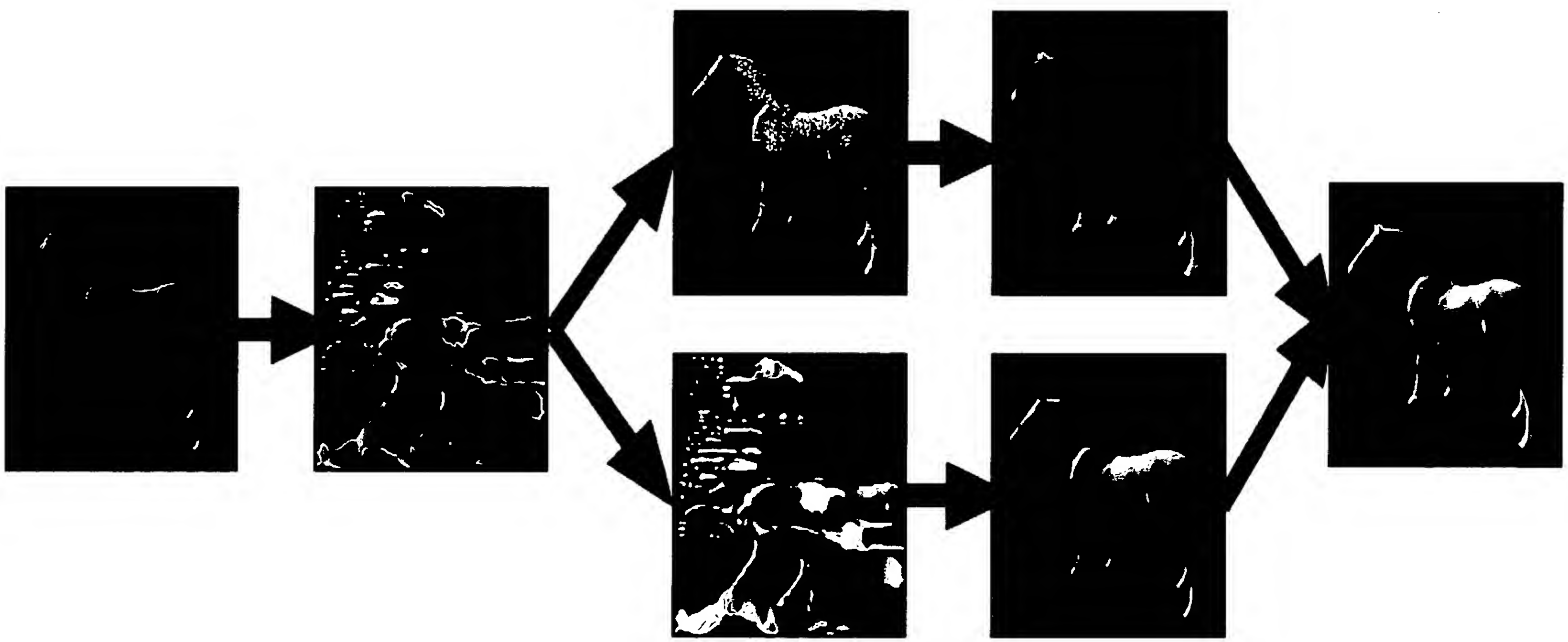
$$E_{in}(x_i)=\frac{1}{\pi}\int_{2\pi}L(x_i,\vec{\omega}_i)(\vec{n}_i\cdot\vec{\omega}_i)F_t(\eta,\vec{\omega}_i)d\vec{\omega}_i$$

Demo



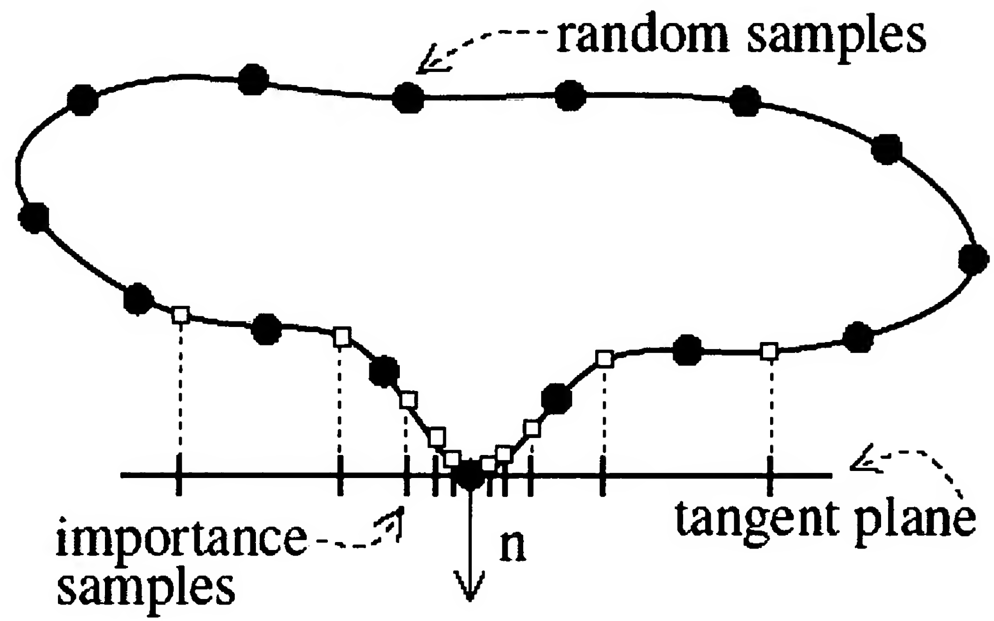
Research on BSSRDF

- Lensch, H. P.A., Goesele, M., Bekaert, P., Kautz, J., Magnor, M. A., Lang, J., and Seidel, H.-P.(2002). Interactive Rendering of Translucent Objects. *Proceedings of Pacific Graphics 2002*, pages 214–224.

- 

Research on BSSRDF

- Mertens, T., Kautz, J., Bekaert, P., Reeth, F. V., and Seidel, H.-P. (2003). Efficient Rendering of Local Subsurface Scattering, *Proceedings of the 11th Pacific Conference on Computer Graphics and Applications*, page 51.



Research on BSSRDF

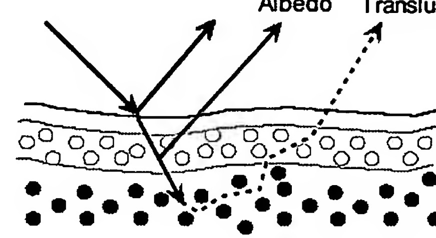
- Hao, X., and Varshney, A.(2004). Real-time rendering of Translucent Meshes. *ACM Transactions on Graphics,* pages 120-142.
- Wang, R., Tran, J., and Luebke, D.(2005).All-Frequency Interactive Relighting of Translucent Objects with Single and Multiple Scattering. In *Proceedings of SIGGRAPH 2005*.

Multiple Scattering | Single Scattering | Multiple and Single Scattering | Diffuse BRDF

Skin Rendering using BSSRDF

- Henrik Wann Jensen. Digital Face Cloning SIGGRAPH'2003 Technical Sketch, San Diego, July 2003
- Weyrich, T.,Matusik, W.,Pfister, H., Lee, J., Ngan, A., Jensen,H.W., and Gross, M. Measurement-Based Skin Reflectance Model for Face Rendering and Editing MERL Technical Report (TR2005-071), July 2005

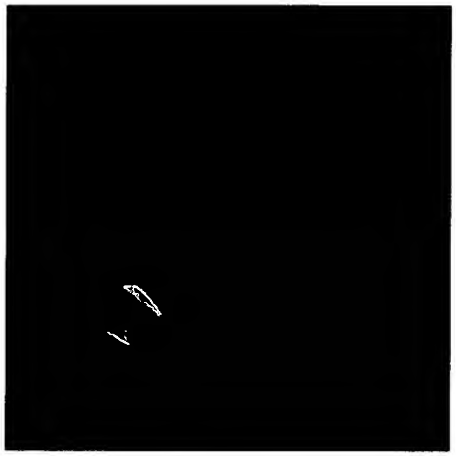
$$L(x_o, \omega_o) = R_{skin}(x_o, \omega_o) + S_{skin}(x_o, \omega_o)$$



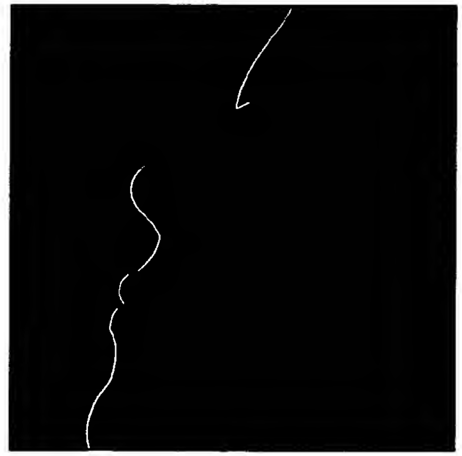
$$R_{skin}(x_o, \omega_o) = \int \mathrm{L}(x_i, \omega_i)(\vec{n}_i \cdot \vec{\omega}_i)\mathrm{F_r}(\eta, \omega_i)F(\omega_i, \omega_o)d\omega_i$$

$$S_{skin}(x_o, \omega_o) = \int\int \mathrm{L}(x_i, \omega_i)(\vec{n}_i \cdot \vec{\omega}_i)\mathrm{F_t}(\eta, \omega_i)S(x_i, \omega_i, x_o, \omega_o)\mathrm{F_t}(\eta, \omega_o)dx_i d\omega_i$$

Skin Rendering using BSSRDF



(d) Oily layer



(e) Subsurface scattering

(f) Final result

Image/Texture Based Approach

- Green, S. Real-Time Approximation to Subsurface Scattering. GPU gems chapter 16.
- Warp lighting
- Rim lighting
  - Realistic Shading of Human Skin in Real time
- Depth map
  - nVIDIA
- Texture Space Diffusion
  - “The Matrix Reloaded“
  - ATI
  - nVIDIA

Warp lighting

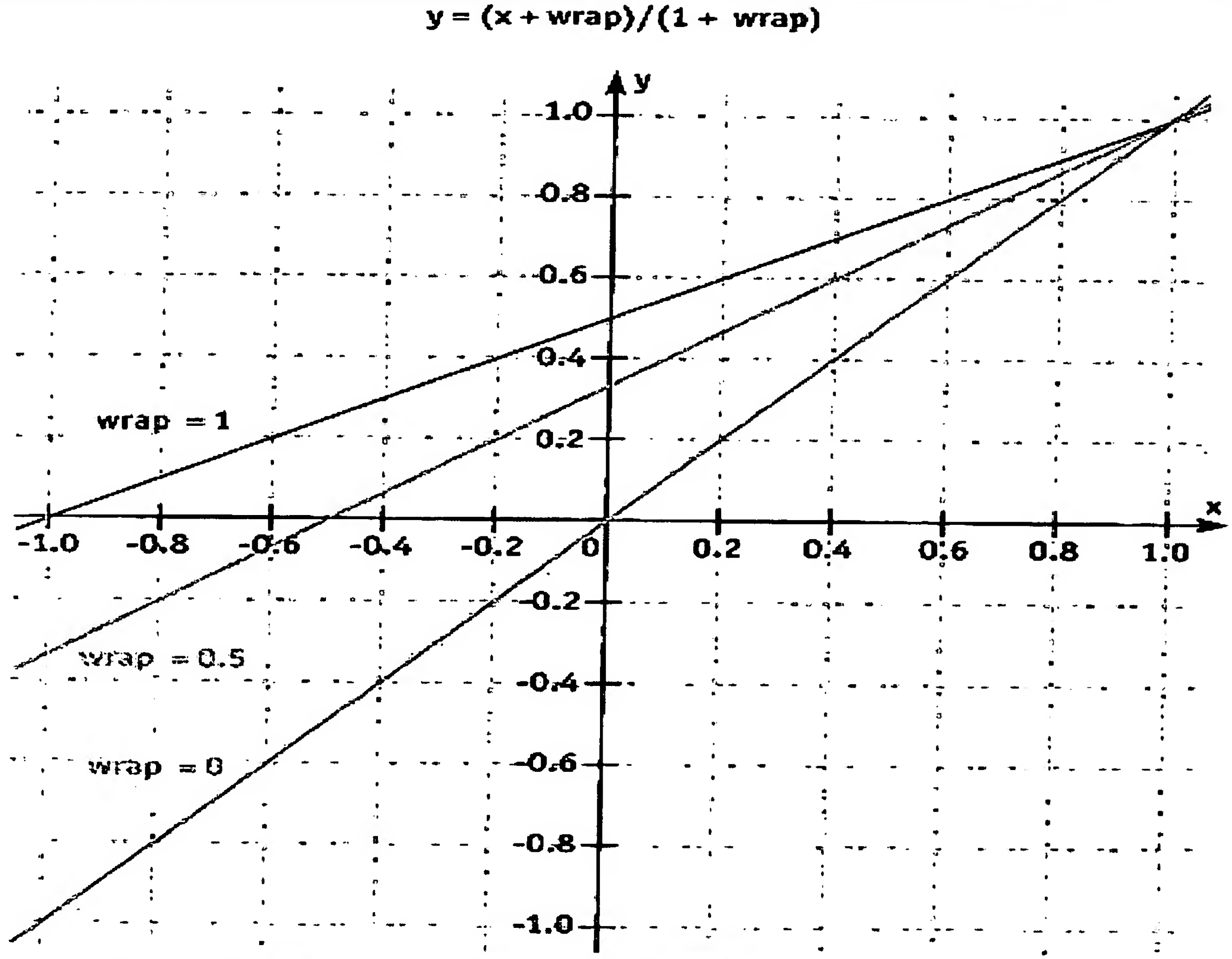
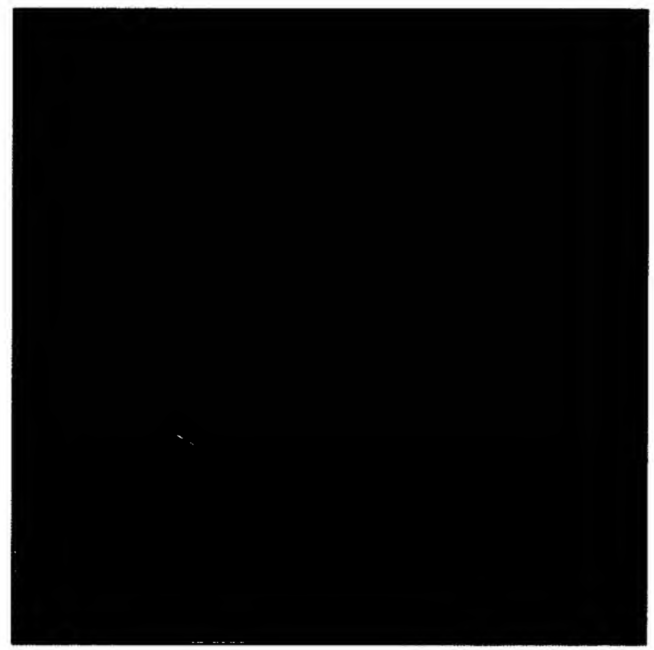


Figure 16-1. Graph of the Wrap Lighting Function

Rim lighting

- 邊緣打光，強化邊緣透射的效果

- Struck, F. Bohn, C.-A., Schmidt, S., and Helzle, V. (2004). Realistic shading of human skin in real time. In Proceedings of the 3rd international conference on Computer graphics, virtual reality, visualisation and interaction in Africa
  - 以Color Texure Map為基礎
  - Local illumination model
  - 利用多個數學式，強化皮膚顯像的特性



Rim lighting

- [ ] Movie Demo

Depth map

- Calculating the depth from view to light

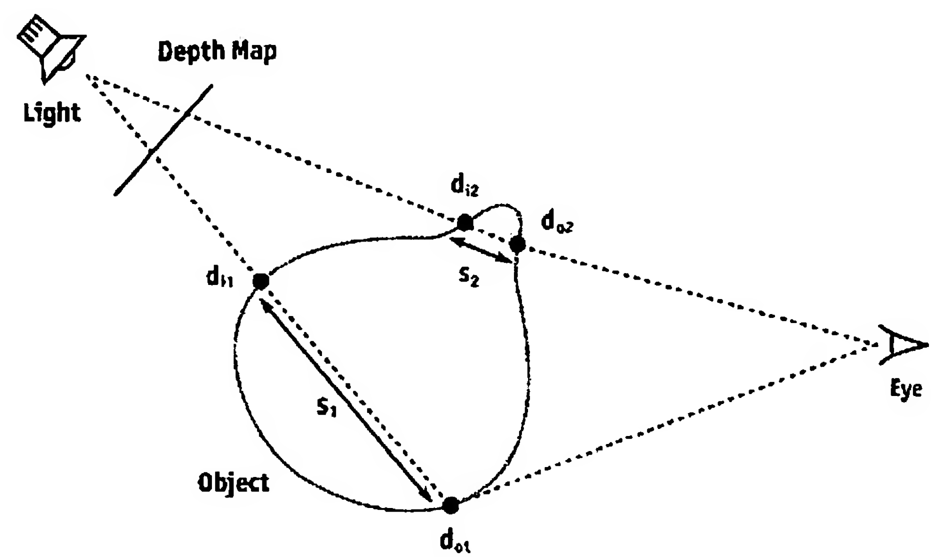
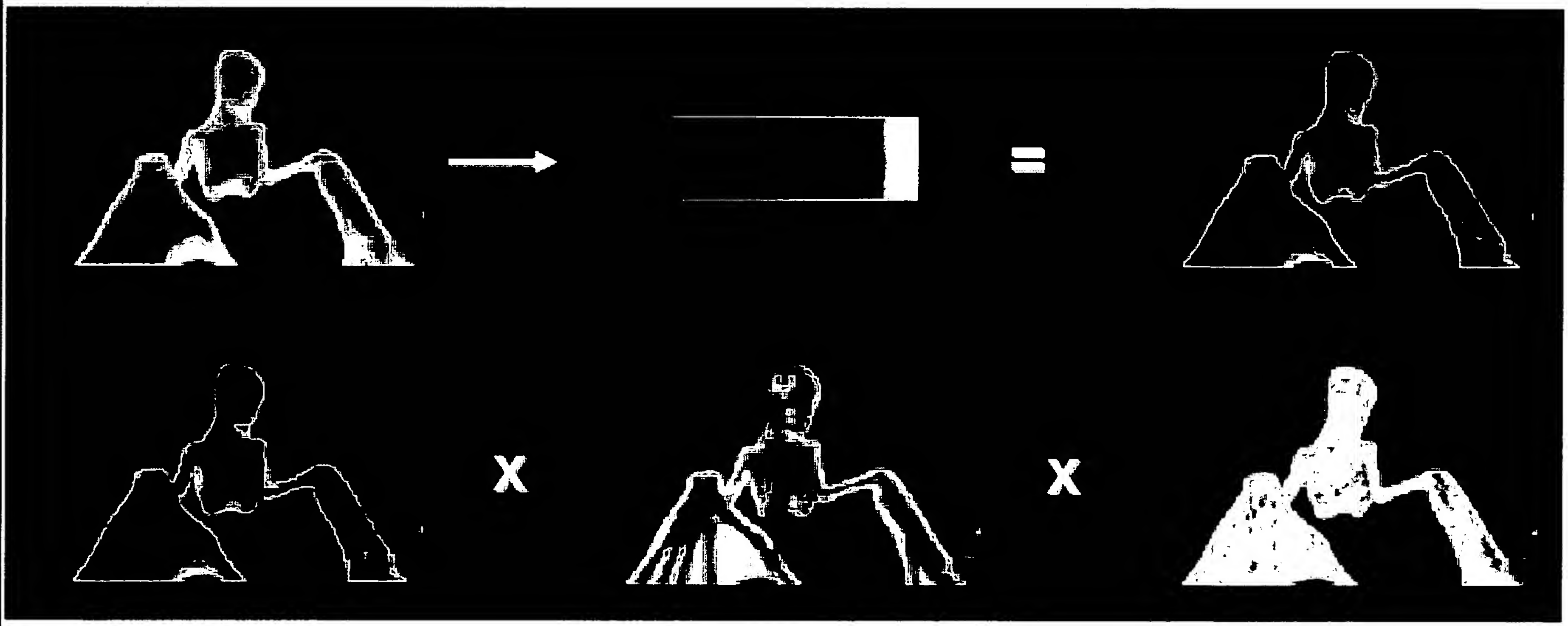


Figure 16-3. Calculating the Distance Light Has Traveled Through an Object Using a Depth Map

- nVIDIA Demo
  - Dawn
  - Luna

nVIDIA-Luna

- Depth Map+Multi-Layer Mapping



nVIDIA-Luna

nVIDIA-Luna

Texture Space Diffusion

- $$L_o(x_o, \vec{\omega}_o) = F_t(\eta, \vec{\omega}_o) \int_A E_{in}(x_i) R_d(\| x_i - x_o \|) dA_{x_i}$$

  $$E_{in}(x_i) = \frac{1}{\pi} \int_{2\pi} L(x_i, \vec{\omega}_i)(\vec{n}_i \cdot \vec{\omega}_i) F_t(\eta, \vec{\omega}_i) d\vec{\omega}_i$$

- Calculating by texture space filter

  $$L_o(x_o, \vec{\omega}_o) = F_t(\eta, \vec{\omega}_o) \sum_i E_{in}(u_i, v_i) R_d(\| x_i - x_o \|) A_i$$

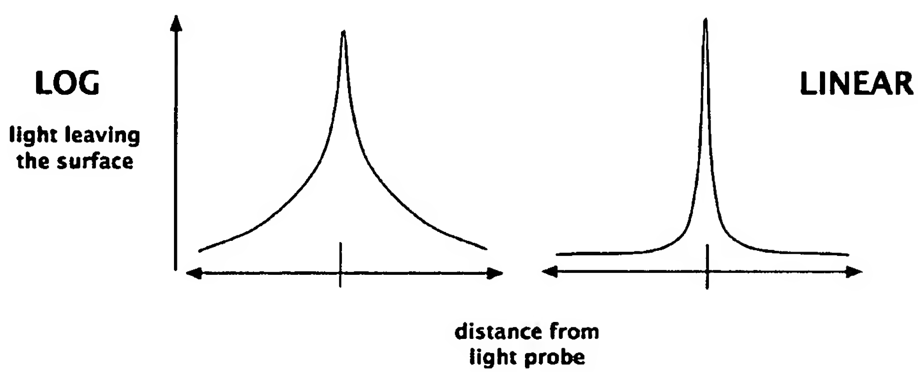
- Research
  - “The Matrix Reloaded“
  - ATI
  - nVIDIA

"The Matrix Reloaded"

- Phase 1 : Render irradiance to texture

Light map

- Phase 2 : Apply Filter to texture



“The Matrix Reloaded“

- Phase 3 : Render final Image accroding to
  - Blurred irradiance map
  - Color map
  - Other else

Real vs. CG

Problem

- Large gap between Realistic and Real-Time
- Realistic algorithm can’t run in Real-Time.
- Real-Time technique doesn’t have very good result.
  - Detail feature need to be taken into account
    - Hair
    - Fine wrinkle
    - mole, pore, spot etc..